Minimum Energy Storage Converters based on a Coupled Magnetic Structure: Design Methodology

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***Abstract* — This paper presents a design methodology for coupled inductor converters designed and operated under the principle of minimum energy storage. This minimum energy storage concept is applied to a coupled inductor converter along with a control strategy that aims to keep constant the sum of input voltages to the magnetic component for every instant of time. If the input voltage is kept constant, output voltage would be also constant for every instant of time and the energy storage in the converter would be minimized. The main advantage of this concept is that a very fast dynamic response can be achieved without operating at very high frequencies, thus maximizing efficiency in a wide load range. Instead of continuous voltage regulation, output voltage can be changed in discrete values, which could be a drawback in some applications. The proposed design methodology is applied in order to design a four-cell prototype and it is validated with an experimental prototype.**

I. INTRODUCTION

The development and growth of technology such as microprocessors, DSPs and other data processing units has led to a demand for very fast power supplies. Besides the need for fast dynamics, it is also necessary to achieve very high efficiency, since many times, such mentioned data processing units are located in mobile devices. A more efficient energy processing in the power supply can contribute to extend mobile devices autonomy.

In order to overcome these problems, many proposed solutions can be found in the state of the art. Among them, multiphase buck converters and multiphase-coupled buck converters ([2, 3]) are two interesting solutions. A comparison between coupled and uncoupled multiphase converters is presented in [5].

This paper proposes a multiple-cell buck converter designed and operated with minimum energy storage. This converter is based on coupled inductor multiphase buck converters with the cells of the proposed converter magnetically coupled using simple transformers (as shown in [4]). Also, output current of the converter is equally distributed among all the cells. An example of an implementation of a four-cell minimum energy storage converter is shown in Figrue 2.

The main purpose of the proposed concept is to minimize the energy stored at the output filter (output inductor + output capacitor). This is possible by ensuring that the converter only works at duty cycles where the ripple cancellation is maximum. At these duty cycles, the sum of the input voltages of all the cells is constant for every instant of time. When applying this minimum energy storage strategy, a very fast dynamic response is achieved without operating at high frequencies. This concept was presented in [1] and it is explained with more detail in section II. In section III a design methodology is developed in order to optimize a given parameter (e.g. power density) or evaluate different configurations of the proposed topology (e.g. different number of cells), which is based on minimum energy storage concept. The validation of this methodology is presented in section IV, while in section V conclusions of the paper are presented.

II. MULTIPLE-CELL MINIMUM ENERGY STORAGE CONVERTER

As said above, the proposed converter is based on coupled inductor multiphase converters. In this kind of solutions, many phases are paralleled and each phase carries an equal part of the output current. Also each phase is coupled with one or more phases by means of the magnetic component of each phase [4]. These solutions can be represented by a magnetic structure with many inputs delivering energy to it (Figure 1). The behaviour of this kind of solutions can be represented by the following equation:

$$v_O = \frac{v_1 + v_2 + \ldots v_n}{n}$$

where n represents the number of phases. This equation states that the output voltage at every instant of time is the sum of the voltages in all the phases. The output current of the converter is given by:

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$$i_O = i_1 + i_2 + ... + i_n$$

The minimum energy storage concept aims at keeping constant, for every instant of time, the sum of the voltages that each cell delivers to the magnetic structure. If the input voltage of the magnetic structure is kept constant, output voltage is also constant and equal to a fraction of the input voltage (depending on the duty cycle). Thus, the value of the filtering elements of the converter can be minimized and therefore energy storage in the converter would be also minimized.

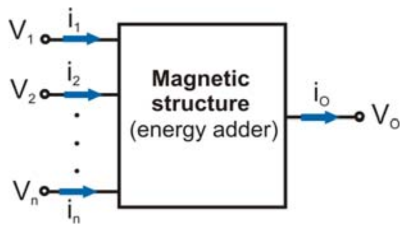
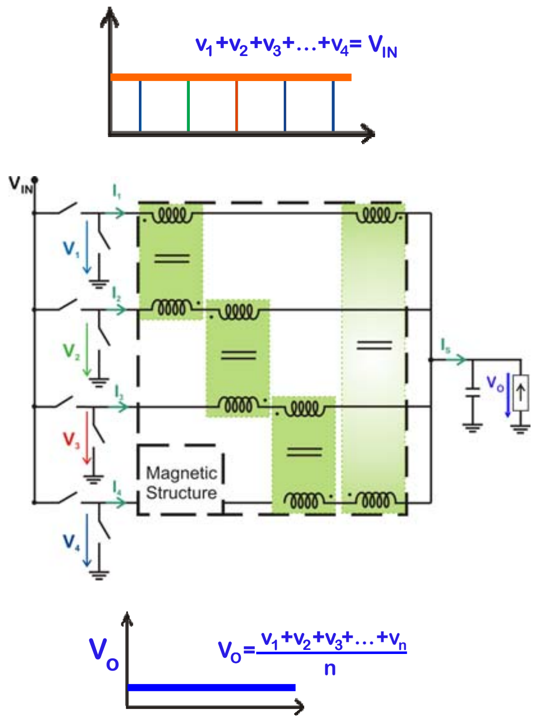


Figure 1. Representation of a multiphase converter with coupled inductors



Figrue 2. If the sum of input voltages to the magnetic structure is kept constant for every instant of time, then the output voltage would be also constant for every instant of time

Since the energy storage is minimized, the dynamic response can be shown to be very fast without having to operate at very high switching frequencies. However, the converter will not have regulation capability.

Constant input voltage (and therefore constant output voltage) can be achieved only in the nodes of the converter. Nodes can be defined as the points of duty cycle where maximum ripple cancellation is achieved. These points are given by:

$$d = k \cdot \frac{1}{n}$$

where k is an integer ranging from *1* to *n-1*. From this equation, it can be seen that for n=4, there are three points of maximum ripple cancellation, where the proposed control strategy can be achieved, therefore, three different output voltage levels (n-1) are available in the case that n=4.

This control strategy was presented in [1] and is summarized in Figrue 2.

III. Proposed Design Methodology

The objective of this design methodology is the evaluation and comparison of different configurations for the proposed minimum energy storage concept. It can be used to design a set of prototypes with specific characteristics (i.e. given magnetic core size, PCB technology) and find the minimum losses operating point.

In order to determine the frequency for minimum losses, a model was developed which accounts for the following:

1) Switching losses. These losses are calculated as in [6] and are defined as follows:

$$P_{SW} = P_{TURN\_ON} + P_{TURN\_OFF} + P_{DRR} + P_{COSS}$$

2) Conduction losses. These losses include losses due to average current and circulating energy losses. Conduction losses are calculated by:

$$P_{COND} = P_{RDSon} + P_{PARASITIC\ PCB\ RESISTANCE} + P_{TRANSFORMER\ WINDING}$$

where P_{RDSon} and $P_{PARASITIC\_PCB\_RESISTANCES}$ are losses due to MOSFETs on-resistance and parasitic resistances of the PCB traces. Losses in transformer windings are given by:

$$P_{TRANSFORMER\_WINDING} = R_{DC} \cdot I_{DC}{}^2 + \sum_n R_{ACn} \cdot I_{RMSn}{}^2$$

3) Core losses. These losses are calculated based on Steinmetz equation:

$$Pv = k \cdot f_{SW}{}^{\alpha} \cdot B^{\beta}$$

k, α and β are parameters related to the chosen magnetic material. It can be seen that this losses are frequency dependent. Total losses would be defined as:

$$P_{TOTAL} = P_{SW} + P_{COND} + P_{CORE}$$

According to this model, it can be seen that switching losses are increased when the switching frequency is raised. Conduction losses are mainly dependent on the average and ripple values of the current. Therefore, increasing the switching frequency decreases the current ripple value and conduction losses are reduced. According to the converter characteristics (magnetizing inductance, magnetic material, MOSFETs, cell number, etc.) there is a frequency for which the sum of switching and conduction losses become minimum. A comparison between model predictions and experimental measurements for 100kHz is shown in Figure 3.a). As it can be seen, the prediction of the model is considered to be acceptable.

Once the losses model proved to be valid, the design methodology was developed. There are many different parameters that could be considered when designing the prototype (cell number, frequency, size and material of magnetic component, etc.). Once initial parameters are set, a series of steps are proposed. However it is necessary to repeat the process with different input parameters in order to compare a set of valid designs with different characteristics.

The proposed steps for the design methodology are as follows:

1) Consider specifications for the converter design: V_{IN}, V_{OUT}, I_{OUT} and consider design input parameters: PCB technology, number of cells, magnetic core and initial current ripple. PCB technology is important since this design optimization is based on PCB integrated transformers.

2) Calculate maximum number of turns for the transformers based on PCB technology and magnetic core size. Having determined the maximum turns number and the material of the magnetic core, the maximum L_{MAG} is known and an estimation of initial f_{SW} and flux density are done.

3) Estimates of initial losses in the magnetic core and DC losses in the transformer windings are made. If these losses are not acceptable, initial turns number can be decreased or current ripple specification can be changed.

4) To obtain a design or a set of designs with acceptable losses based on this initial losses calculation.

5) Next step is to model the obtained transformer (or transformers) in the PEmag modelling tool [7] and obtain an AC resistance of transformer windings and leakage inductance in order to include these parameters into the model. At this point an initial f_{SW} has been chosen and a set of MOSFETs are considered.

6) The parameters of this set of MOSFETs should be incorporated in the model at this point and a complete losses calculation can be done for different frequencies with all the chosen MOSFETs. From these results it should be possible to choose the design that results with the minimum losses.

7) In order to evaluate and compare different designs, one or more input parameters (magnetic structure, ripple, cell numbers, PCB technology) should be changed and the design loop should be followed again.

IV. Four-Cell experimental prototype: design methodology validation

A four-cell prototype was developed by applying design methodology.

The design parameters of this prototype are: V_{IN}=12 V, V_{OUT}=3 V, I_{OUT}= 35 A, the use of planar magnetic cores (pair of E14) and the integration of the windings into the PCB were design inputs for this prototype. By applying the step-by-step methodology, and considering the above mentioned characteristics, a set of acceptable designs was obtained. Some of the results that where obtained applying steps 1 through 7 are presented in Table 1 and Table 2.

After these steps are followed, a set of different designs should be obtained. When input parameters are changed, a comparison among designs with different characteristics (size, operating frequency, losses) can be done.

From the set of acceptable designs presented in Table 1, it can be seen that, by considering DC winding losses, designs with magnetizing inductances corresponding to two and three turns are interesting for further evaluation. Between these two options (L_{MAG}=11.5uH or 5.1uH) the design with L_{MAG}=11.5uH is chosen. The design with two turns and L_{MAG}=5.1uH needs higher frequency to achieve the chosen current ripple. The next step is to apply step 6. Three MOSFETs have been considered and its parameters have been incorporated to the model. The data that resulted from this evaluation are presented in Table 2. As it can be seen, the design for L_{MAG}=11.5uH (N=3) achieves the desired current ripple at lower frequency which results in lower losses when the calculation of total losses is done. The higher frequency needed in the case for N=2 raises the total losses account in spite of the smaller DC losses in transformer windings. Therefore the design for L_{MAG}=11.5uH is the design chosen for implementation. A graph with the calculated losses for different frequencies for this design is shown in Figure 3.b (losses against frequency) and a picture of the experimental prototype is shown in Figure 3.c.

Steady state and dynamic tests were run using the optimized prototype. The measured efficiency for this prototype is presented in the curve in Fig 4a) and the

TABLE 1

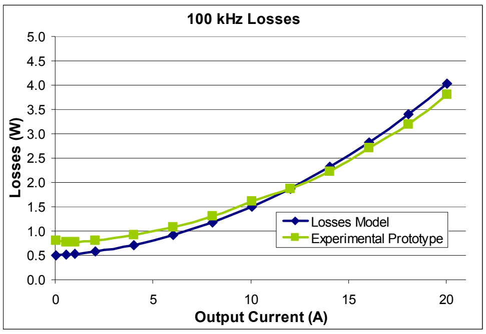
SET OF ACCEPTABLE DESIGNS OBTAINED WHEN APPLYING STEPS 1 THROUGH 5. PW STANDS FOR PARALLEL WINDINGS. LLK STANDS FOR LEAKAGE INDUCTANCE OBTAINED FROM PEMAG MODEL. PEMAG AC RESISTANCE ACCOUNTS THE RESISTANCE AT F_{SW} FOR ΔI, WHICH SHOWS THE FREQUENCY NECESSARY TO ACCOMPLISH THE CHOSEN CURRENT RIPPLE

Turns	Lmag (µH)	PW	WindingRDC (mΩ)	fSW for ΔI (kHz)	LLK (nH)	DC Winding losses (W)	PEmag AC resistance(mΩ)
4	20.5	0	10.9	140	4.9	5.3	13
3	11.5	2	4.09	250	1.9	2.0	6.8
2	5.1	3	1.8	550	0.8	0.9	3.8
1	1.2	6	0.4	2000	0.2	0.2	3.2

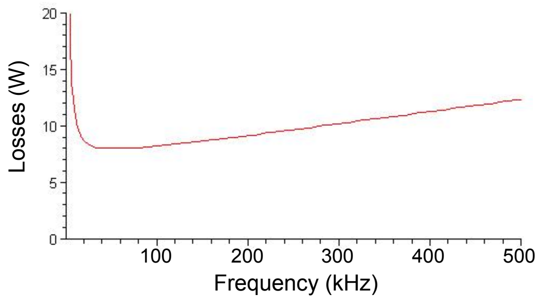
TABLE 2

TOTAL LOSSES CALCULATION WITH THREE DIFFERENT MOSFETS FOR CANDIDATE PROTOTYPES WITH A MAGNETIZING INDUCTANCE OF 11.5µH (N=3) AND 5.1uH (N=2) WITH ΔI=400mA . BSC042N03 MOSFETS ARE CHOSEN.

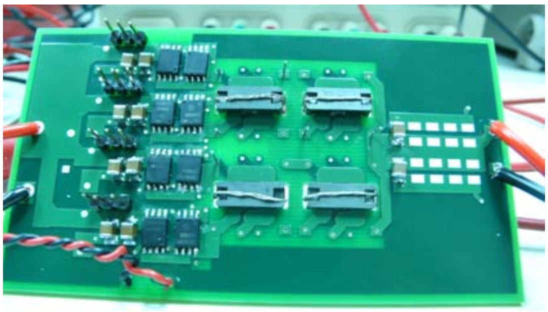
MOSFET	package	R_{DSon} (mΩ)	Ciss (pF)	Coss (pF)	Losses for Δi (W)	
					N=3	N=2
IRF7831	SOIC8	3.6	6240	980	10.1	15.0
Si7136DP	PowerPak	3.2	3380	797	11.1	15.9
BSC042N03	TDSON8	4.2	4300	1300	9.8	12.2



a)



b)



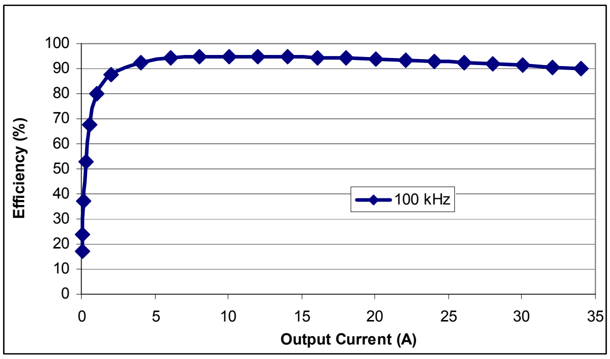
c)

Figure 3. a) Comparison between losses model prediction and losses measurement for 100kHz. b) Losses calculation for different frequencies (up to 500kHz). c) Picture of experimental prototype

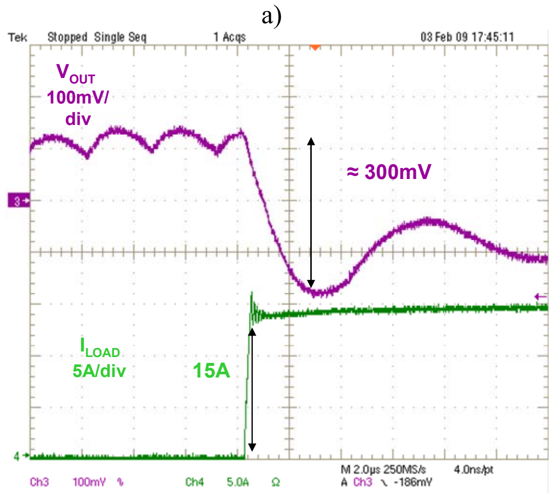
dynamic response is shown in Fig 4b). **It can be seen that efficiency is very high for a wide load range, from 3 A to 30 A efficiency is greater than 90%, along with this efficiency, the dynamic response is also very fast.** The output voltage deviation under a 15 A load step (60A/µs) is less than 300 mV which represents 10% of total output voltage with an output capacitor of four 22µF ceramic capacitors. Input capacitor is a set of four 22uF MLC Capacitors and one 70µF OSCON. Output capacitance, as said above is comprised of four 22µF MLCC.

V. CONCLUSIONS

A four-cell minimum energy storage converter has been designed, this converter is based on coupled inductor multiphase converter but applying a constant input – constant output control strategy that allows the



a)



b)

Fig 4. **a)** Efficiency measurement for experimental prototype: efficiency is greater than 90% for a wide load range (from 3 A of output current to 30 A and with a peak efficiency of 94.8%) **b)** Measured output voltage deviation (50 mV/div) under a 15A load step with slew rate of 60A/us (5 A/div).

minimization of the output filter of the converter, and therefore the energy storage in the converter is minimum.

This minimum energy storage provides a very fast dynamic response with low operating frequency and a very high efficiency thanks to the low operating frequency, although it limits the regulation capability of the converter.

A design methodology was presented and proven to be useful, allowing the evaluation of different parameters (PCB technologies, MOSFETs, different combinations of L_{MAG} and operating frequency) and resulting in the design of a converter with the inductors integrated in the PCB. The design methodology provides a set of solutions where each solution determines a number of cells, a switching frequency, a magnetic structure design and selected MOSFETs. The selected solution is a trade-off among losses, cost, size and complexity.

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